A SIMPLIFIED METHOD OF CORRECTION FOR KINETIC ENERGY EFFECTS ON THERMOCOUPLE READINGS IN A GAS STREAM

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1. BACKGROUND

Traditionally, the heat balance on a thermocouple in a gas stream is set up in terms of convection to the thermocouple tip and radiation from it. This heat balance is at the heart of routine thermocouple work on gases and the calculation, where necessary, of 'radiation corrections'. Any basic heat transfer text [e.g. 1] can be consulted for details of this.

There is in principle another factor which operates, namely the conversion of kinetic energy to thermal at the thermocouple tip. One seldom encounters any mention of this even in texts devoted to temperature measurement, though it was pointed out by Moffatt over 40 years ago [2] that full analysis of energy balance at a thermocouple tip has to include it even if, in almost all situations of practical interest, it is negligible.

Moffatt [2] gives the following equation for the temperature effect of the extent of recovery of kinetic energy:

$$T_J = T_T\left\{1 - (1 - \alpha)\frac{[(\gamma - 1)/2]\, M^2}{1 + [(\gamma - 1)/2]\, M^2}\right\}$$

where T_T is the thermocouple tip temperature, T_J the gas stream temperature, α the recovery factor, γ the ratio of principal specific heats (= 1.4 for air) and M the Mach number. For forced convection under turbulent conditions, the correlation:

$$\alpha = Pr^{1/3}$$

where Pr is the Prandtl number, is a reasonable approximation, and for air at oven temperatures Pr = 0.7, giving $\alpha = 0.89$, and for air $\gamma = 1.4$.

The above is an 'end-user' approach to estimating the error utilising a not particularly transparent equation. It is of interest, and possible value to the thermocouple user, to complement this by application of the First Law of Thermodynamics for an open system to gas flow at a thermocouple tip. This will provide insights into the sorts of gas flow speeds necessary for kinetic energies to become comparable to thermal energies and, also, a suitable method of correction.

2. AN APPROACH USING THE FIRST LAW

The First Law for an open system – one which can exchange both energy and mass with its surroundings – is given in many texts [e.g. 3] as:

$$m'[0.5c_2^2 + gz_2 + h_2] = \boldsymbol{Q} + \boldsymbol{W} + m'[0.5c_1^2 + gz_1 + h_1]$$

where subscript 1 denotes entry and subscript 2 denotes exit, m' is the mass flow rate (kgs^{-1}), c the velocity (ms^{-1}), z the height from a fixed reference level (m), g the acceleration due to gravity = 9.81 ms^{-2}, h the specific enthalpy of the fluid (Jkg^{-1}), $\boldsymbol{W}$ the rate of work on or by the fluid (W), and $\boldsymbol{Q}$ the rate of heat transfer to or from the fluid (W).

In adapting this to our application, we note that potential energy effects are nil, and that since a thermocouple has no moving parts $\boldsymbol{W} = 0$. When the above equation is applied to nozzles and similar devices, the assumption is usually made that conditions are adiabatic, i.e., the system, which comprises the gas and nozzle, transfers no heat to and receives no heat from the surroundings, that is, $\boldsymbol{Q} = 0$. Though the present author has not been able to confirm this, the appearance in Moffatt's equation of the ratio of principal specific heats (symbol γ) strongly suggests the assumption of adiabatic conditions in his formulation. The steady flow equation above then reduces to:

$$c_1^2 - c_2^2 = 2(h_2 - h_1)$$

where subscript 1 denotes approach to the thermocouple and subscript 2 departure from the thermocouple. On the principle that the proportion of kinetic energy recovered is $Pr^{1/3}$:

$$0.7^{1/3} = 0.9 = (c_1^2 - c_2^2)/c_1^2 \Rightarrow c_2 = 0.3c_1$$

This gives:

$$c_1^2(1 - 0.09) = 2(h_2 - h_1) = 2c_p\Delta T$$

where c_p is the specific heat of air at constant pressure (≈ 1000 $Jkg^{-1}K^{-1}$) and ΔT the rise in temperature of the thermocouple tip due to kinetic energy recovery.

Imagine then air flowing past a thermocouple tip at Mach 1 (330 ms^{-1}). This gives:

$\Delta T = 50K$

that is, there will be a 50 K error in the thermocouple reading due to the conversion of kinetic energy to thermal. What speed would be required to cause a 1 K error? This is easily calculable from:

$c_1 = (2c_p/0.91)^{0.5} = 47 \text{ m s}^{-1}$

As already stated, there is little in the thermocouples literature which deals with errors due to kinetic energies. There is however an 'oral tradition' that speeds of the order of 10 m s^{-1} are required for a 1K error and the above calculation is consistent with this. An error of 1K might not be worth correcting for in that it is smaller than the intrinsic uncertainty in the thermocouple reading and, possibly, smaller than radiation errors. A speed of 10 ms^{-1} is the threshold above which possible kinetic energy effects need to be noted.

By reason of there being a temperature-independent c_p, the approach herein gives the same correction for any flow speed irrespective of temperature. This is not true of the Moffatt treatment and there is scope for examining the two together in order to ascertain at what temperatures the Moffatt treatment gives the same results as the present one and the significance of any departure of results from the two methods in other temperature ranges.

Three further points need to be made. One is that if one makes the approximation:

$c_2 \approx 0$

that is, full recovery of kinetic energy, the effect on the calculation is not great. The previous calculation repeated for these circumstances gives a ΔT of 55K, only 5 K higher than for a recovery factor of 0.9.

Secondly, readers should be aware that in most applications of thermocouples, kinetic energy effects are insignificant. For example, speeds of about 10 ms^{-1} are common for gases and vapours in pipes in chemical processing, and such speeds, as we have seen, are such that kinetic energy effects are likely to be smaller than other sources of error. In fan-assisted laboratory ovens, flow speeds at fan exit might well be of the order of a metre per second, being reduced significantly on expansion into the work space of the oven. Here again kinetic energy effects, though calculable, are not of practical importance. Finally, it is difficult to see how in natural, rather than forced, convection with gases, kinetic energy effects could ever be important.

3. CONCLUDING REMARKS

Thermocouple applications requiring a kinetic energy correction are fairly few and far between but not so much so as to justify any statement that the exception proves the rule. For example, such corrections will certainly be required for a thermocouple attached to the outside of an aircraft fuselage. The treatment herein provides a simplified means of estimating the correction required. This can be factored in with other uncertainties in estimating the total plus-or-minus on the thermocouple temperature reading.

REFERENCES

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